LONG-TERM EARTHQUAKE PREDICTION FOR THE KURIL-KAMCHATKA ARC FOR 2006-2011 AND SUCCESSFUL PREDICTION FOR THE MIDDLE KURIL ISLAND EARTHQUAKE, 15.XI.2006, M_S = 8.2

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ABSTRACT

Results are reported from continuous long-term earthquake prediction work for the Kuril-Kamchatka island arc using the patterns of seismic gaps and the seismic cycle. A five-year forecast (April 2006 to April 2011) for all portions of the Kuril-Kamchatka seismogenic zone is presented. According to this, the most likely locations of future M ≥ 7.7 earthquakes include the Petropavlovsk-Kamchatskii area where the probability of an M ≥ 7.7 earthquake causing ground motions of intensity VII to IX in the town of Petropavlovsk-Kamchatskii is 48 % for 2006-2011, and the area of Onekotan I. and the Middle Kuril Islands where the probability of an M ≥ 7.7 earthquake was estimated as 26.7 %. The forecast was fulfilled on November 15, 2006, when an M_S = 8.2, M_W = 8.3 earthquake occurred in the Middle Kuril Islands area. An updated long-term forecast is presented for the Kuril-Kamchatka arc for the period from November 2006 to October 2011. These forecasts provide good reasons to enhance seismic safety by strengthening buildings and structures in Kamchatka.

INTRODUCTION

Long-term earthquake prediction is one of the most important lines of research in the work of prediction and assessment of earthquake hazard. The Kuril-Kamchatka island arc is the most active seismic region in Russia. The seismicity observed there is of the highest intensity found on Earth. It was for this region and other similar structures that in 1965-1968 Fedotov put forward a method of long-term earthquake prediction based on patterns of likely locations for future great earthquakes (seismic gaps) and on the seismic cycle concept [9, 10]. The method has been continually used and refined over time. Twenty basic works dealing with the method and a review of the 1962-2002 results can be found in [12]. The most recent reference in that book provides a forecast for 2001-2005 and describes the state of the art as of 2002 [16]. An evaluation of the previous forecasts and a forecast for 2004-2008 can be found in [14].

Long-term earthquake prediction involves the study of seismicity patterns, the development and refinement of long-term forecasts, as well as acquisition of such data on earthquake hazard as are required for preparedness measures to reduce human and material losses. The results derived by the method were the basis for six governmental decrees and decisions adopted in 1986-2001 and later on regarding seismic preparedness in Kamchatka ([12] and elsewhere).

At present the method is being used to forecast several seismicity characteristics of the Kuril-Kamchatka island arc for the next five years. The locations of future great (M ≥ 7.7) earthquakes are identified (seismic gaps); these are segments of the arc where no earthquakes of this size have occurred during the past 80 years. The most active strip in the Kuril-Kamchatka seismogenic zone, generating earthquakes in the depth range 0-80 km, of length 2100 km and width 100 km, is divided into 20 portions on the average to predict for these portions the phases of the seismic cycle, to indicate the seismic gaps, to determine the relative hazards presented by these gaps, to predict the seismicity rate A_{10} (the annual number of small, i.e., K_S = 10 or M = 3.2, earthquakes per 10^3 km^2 area, the notion of K_S being defined in [11]), the magnitudes M of earthquakes to be expected with probabilities 0.8, 0.5, and 0.15, the maximum credible magnitudes, and the probabilities of great (M ≥ 7.7) earthquakes, see [12, 14, 15, 16, 20-22] and elsewhere. The long-term forecasts for great earthquakes, as developed during 1965-2005, have a success rate of 0.8-0.9 [12].

Long-term earthquake forecasts are developed in application to the next five years, because the parameters that underlie the forecasts are derived from data for the preceding five years, their values are predicted for the next five years, and finally, because M ≥ 7.7 earthquakes occur once every five years in the entire Kuril-Kamchatka arc on the average (see [9, 12, 14, 15, 16, 20, 21] and elsewhere), also Section 1 in this paper.

Forecasts are updated every six months, or more frequently when large earthquakes occur and the seismicity parameters for the preceding five years are significantly affected. The resulting forecasts are compared with forecasts derived by other techniques, say, M8 [3, 7, 14-17, 20, 22 and elsewhere].

The present method can also be used for other regions worldwide that have similar structure, geodynamics, and seismotectonics. One recent example of using the method in other regions is provided by [14] where a retrospective earthquake forecast was developed for the September 25, 2003, M = 8.1 Hokkaido earthquake.

The long-term forecast for the Kuril-Kamchatka arc for the period 2001-2005 is given in [16] and that for 2004-2008 in [14]. The present paper contains a forecast developed in April 2006 for the period April 2006 to April 2011, see Section 2 later in this paper.

Eight months elapsed since the forecast was developed, when an M_S = 8.2, M_W = 8.3 earthquake occurred in the Middle Kuril Is. area on November 15, 2006. This was the largest event to have occurred at the Kuril-Kamchatka arc since the December 5, 1997, M = 7.8-7.9 Kronotskii earthquake [17, 22]. The Middle Kuril earthquake occurred according to the long-term forecasts developed for 2001-2005, 2004-2008, and for the period April 2006 to April 2011 [9, 10, 12, 14 and elsewhere]. (Several investigators have thought an M ≥ 7.7 earthquake to be impossible in the area, see [5, 8] and elsewhere). This successful confirmation of a long-term forecast is discussed in Section 3. First forecasts of large (M ≥ 6) aftershocks following the Middle Kuril earthquake are also provided in Section 5. An updated long-term forecast for the period November 2006 to November 2011 was developed after the Middle Kuril earthquake and the first ten days of its aftershock sequence; the forecast incorporated the changes in the previous seismic gaps in the Middle Kuril Is. area and the resulting rearrangement in the probabilities of M ≥ 7.7 earthquakes for the other portions of the Kuril-Kamchatka seismogenic zone, see Section 4.

Section 5 contains some supplementary material, discusses the results of this work and improvements on the technique, as well as reports the practical applications of the forecasts.

The Conclusion lists the main results.

1. ON THE DEVELOPMENT OF LONG-TERM EARTHQUAKE FORECASTS FOR THE KURIL-KAMCHATKA ARC FOR THE PERIODS APRIL 2006 TO APRIL 2011 AND NOVEMBER 2006 TO OCTOBER 2011

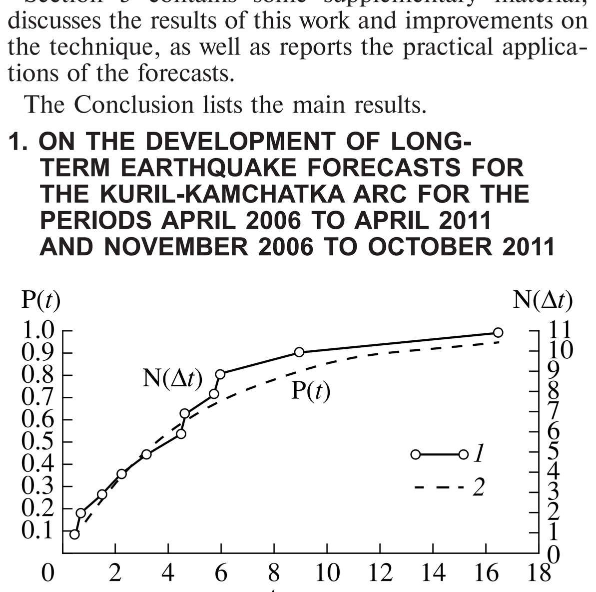

Fig. 1. Number N(Δ*t*) of M ≥ 7.7 Kuril-Kamchatka earthquakes as a function of the associated interevent interval Δ*t* and the probability of occurrence for such earthquakes P(*t*) as a function of waiting time *t*: (*1*) empirical plot showing the distribution of the number N of recorded earthquakes in relation to time interval Δ*t*, years based on the eleven Δ*t* intervals observed in 1952-2006; (*2*) theoretical plot of probability of earthquake occurrence P(*t*) as a function of waiting time *t*, years calculated from the Poisson distribution $P(\Delta t \le t) = 1 - e^{-\lambda t}$ with λ = 0.2.

The long-term earthquake forecast for the Kuril-Kamchatka arc for April 2004 to March 2009 was given in [14]. Afterwards the forecasts were updated three times every six months in 2004-2005. They were developed for the following five-year intervals: November 2004 to October 2009, June 2005 to May 2010, and September 2005 to September 2010. Each such update used seismological data for the five preceding years, the time window and the data set being varied by 1/5. The method of calculation was being refined.

2. LONG-TERM EARTHQUAKE FORECAST FOR THE KURIL-KAMCHATKA ARC, PERIOD APRIL 2006 TO APRIL 2011, MADE IN MARCH 2006

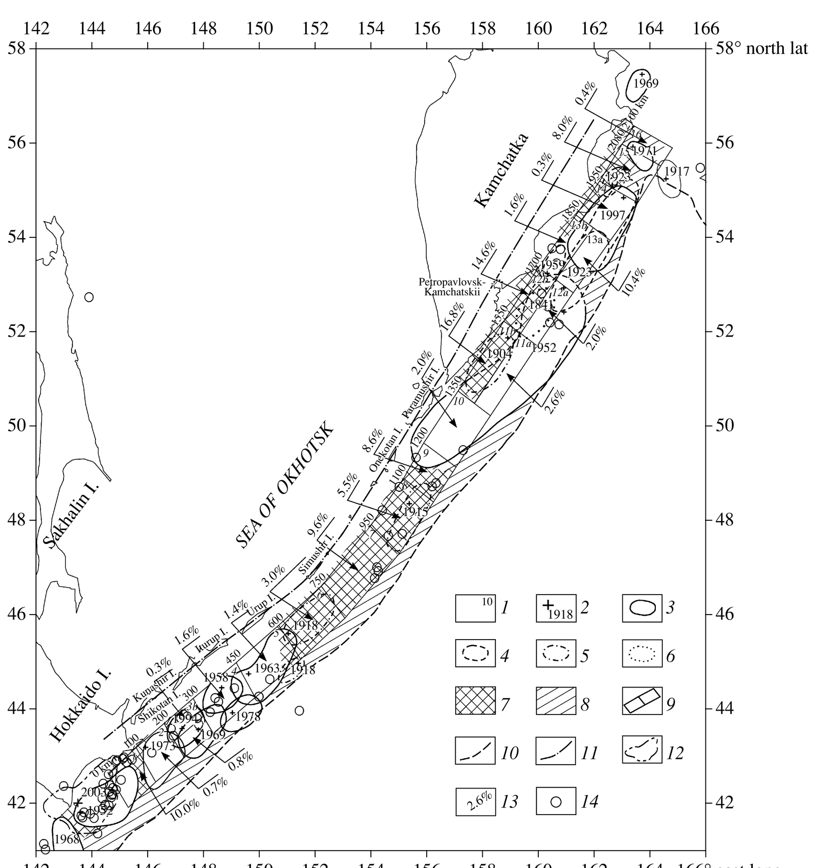

Fig. 2. Map showing the long-term earthquake forecast for the Kuril-Kamchatka arc for the period April 2006 to April 2011, the rupture areas of the 1904-2006 M ≥ 7.7, Kuril-Kamchatka earthquakes, H = 0-80 km, and the probabilities for the occurrence of such earthquakes during the period April 2006 to April 2011 in all portions of the prediction strip: (*1*) portion number, (*2*) instrumental epicenters of M ≥ 7.7 main shocks, (*3*) boundaries of M ≥ 7.7 earthquake rupture areas found to within 10 km, (*4*) segments of these boundaries when determined to lower accuracy, (*5*) probable rupture areas of the 1904-1918 M ≥ 7.7 earthquakes, (*6*) inferred rupture area of the 1841 earthquake, (*7*) the most probable locations of future M ≥ 7.7 earthquakes, (*8*) possible locations of such earthquakes, (*9*) boundary of prediction portions, (*10*) trench axes, (*11*) axis of the Kuril-Kamchatka volcanic belt, (*12*) boundary of the September 25, 2003, M = 8.1 earthquake rupture area, (*13*) probabilities of M ≥ 7.7 earthquakes for April 2006 to April 2011, (*14*) epicenters of M ≥ 5.5, H = 0-80 km earthquakes which occurred between March 2001 and March 2006. The average probability for the occurrence of M ≥ 7.7 Kuril-Kamchatka earthquakes in the same location during 5 years is 3.6-4.2%.

Table 1. Long-term earthquake forecast for the Kuril-Kamchatka arc for the period April 2006 to April 2011 (H ≥ 80 km) based on the parameters A_{10}, D, A_{11}, and a comparison with the October 2004 probabilities of great earthquakes.

			Phase of the cycle and its estimate from the 2001–2006 data (March 2001 to March 2006)					Forecast for April 2006 to April 2011								Forecast for September 2004 to September 2009	
								A_{10} (P ~ 0.7)									
Portion	Δ, km	Location	Phase	$P_1 = P(A_{10})$	$P_2 = P(D)$	$P_3 = P(A_{11})$	$B = (P_1P_2P_3)$	A_{10}	$A_{10} \pm \sigma$	P ~ 0.8	P ~ 0.5	P ~ 0.15	M_{max}	$P(M \ge 7.7)$%	Likely sequence	$P(M \ge 7.7)$%	Likely sequence
1	0–100	Cape Sirikha to Nemuro Peninsula	III	0.21	0.01	0.94	0.002	1.2–3	0.8–4.5	6.0	6.5	7.0	7.8	**10.0** (3.9)	**4** (7)	13.2	2
2	100–200	Nemuro Peninsula to Zelenyi I.	II					1.2	0.8–1.9	5.8	6.3	6.8		**0.7** (0.5)		0.6	
3*a*	200–300	Shikotan I., SE	II					1.2	0.8–1.9	5.7	6.2	6.7		**0.8** (0.6)		0.7	
3*b*	200–300	Shikotan I., NW	I					2.1→1.4	0.9–3.1	6.0	6.4	6.9		**0.3** (0.2)		0.3	
4	300–450	Iturup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		**1.6** (1.4)		1.5	
5	450–600	Vries Strait to Urup I.	II					1.2	0.8–1.9	5.9	6.4	6.9		**1.4** (1.1)		1.3	
6	600–750	Cape Castricum to Bussol' Strait	III?	0.98	0.98	0.73	0.70	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	**3.0** (7.7)	**9** (5)	1.4–4.4	9
7	750–950	Simushir I. to Kruzenshtern Strait	III?	0.98	0.54	0.86	0.45	1.2–3	0.8–4.5	6.2	6.7	7.2	8.2	**9.6** (11.7?)	**5** (3)	9.4	5
8	950–1100	Shiashkotan I.	III?	0.99	0.58	0.95	0.55	1.2–3	0.8–4.5	6.0	6.5	7.0	8.0	**5.5** (3.5)	**8** (8)	7.2	7
9	1100–1200	Onekotan I. to Third Kuril Strait	III	0.87	0.16	0.90	0.13	1.2–3	0.8–4.5	6.0	6.4	7.0	7.9	**8.6** (5.8)	**6** (6)	7.7	6
10	1200–1350	Paramushir I. to Cape Lopatka	II					1.2	0.8–1.9	5.9	6.4	6.9		**2.0** (2.7)		1.9	
11*a*	1350–1550	Southern Kamchatka, SE	II					0.8	0.6–1.1	5.8	6.3	6.8		**2.6** (3.6)		2.5	
11*b*	1350–1550	Southern Kamchatka, NW	III	0.64	0.87	0.25	0.14	1.3–3	0.8–4.5	6.0	6.5	7.0	8.0	**16.8** (18.3)	**1** (2)	10.6	4
12*a*	1550–1700	Avacha Bay to Cape Shipunskii, SE	II					1.2	0.8–1.9	5.7	6.2	6.7		**2.0** (2.7)		1.9	
12*b*	1550–1700	Avacha Bay to Cape Shipunskii, NW	III	0.20	0.79	0.19	0.03	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	**14.6** (20.5)	**2** (1)	19.6	1
13*a*	1700–1850	Kronotskii Bay, SE	III?	0.89	0.82	0.37	0.27	1.2–3	0.8–4.5	5.9	6.4	6.9	8.0	**10.4** (3.6)	**3**	5.3	8
13*b*	1700–1850	Kronotskii Bay, NW	II					2.6	1.7–3.9	5.9	6.4	6.9		**1.6** (1.3)		1.5	
14	1850–1950	Kronotskii Peninsula	I					3.1→1.9	1.2–4.5	6.0	6.5	7.0		**0.3** (0.2)		0.2	
15	1950–2050	Kamchatskii Bay	III?	0.32	0.69	0.83	0.18	1.2–3	0.8–4.5	6.0	6.5	7.0	7.9	**8.0** (8.5)	**7** (4)	12.9	3
16	2050–2100	Kamchatskii Peninsula	II					0.8	0.6–1.1	5.7	6.2	6.7		**0.4** (0.3)		0.3	
Estimate of critical probability values				0.062	0.308	0.06	0.0012							Σ = 100.0		Σ = 101	

Note: This table contains forecasts of seismicity characteristics for April 2006 to April 2011. Probable phases of the seismic cycle are indicated for all the twenty portions. Index III marks those portions where no M ≥ 7.7 earthquakes have occurred during the last 80 years and where the probability that the final phase III of the seismic cycle has set in is considerable. Question marks are attached to those portions where the probability of such an event is lower. B is a parameter that shows the relative hazard of a seismic gap; A_{10} is seismicity rate; P ~ 0.8, 0.5, and 0.15 are the probabilities of M = 5.7-7.2 earthquakes; Mmax is the maximum credible magnitude; P(M ≥ 7.7) denotes predicted probabilities of great earthquakes. The values of P(M ≥ 7.7) in parentheses denote those for 2001-2005. The average long-term value is P(M ≥ 7.7) = 3.6-4.2%.

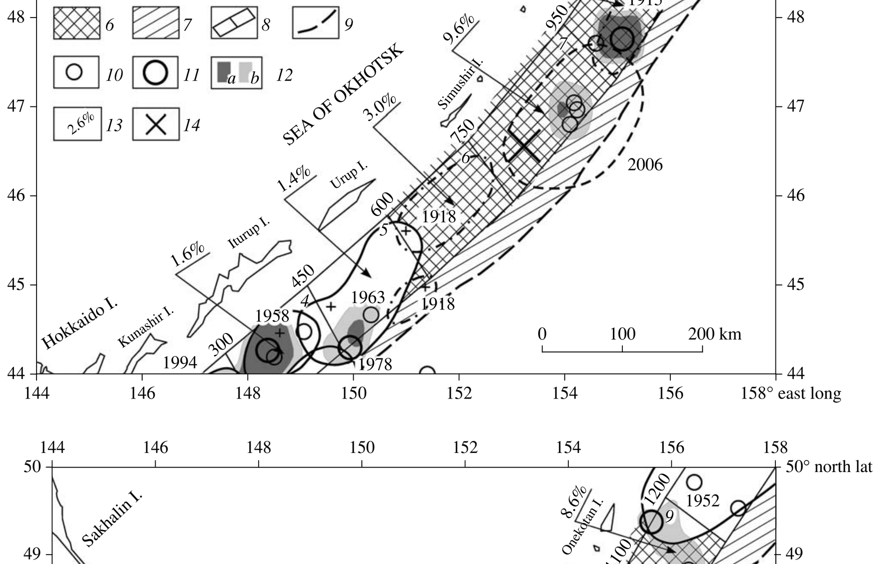

Fig. 3. Map showing the rupture areas of the 1915-2006 M ≥ 7.7 Kuril-Kamchatka earthquakes with depth H = 0-80 km, the seismic gaps, isolines of 1-B based on the March 2001 to March 2006 data, as well as earthquake epicenters for this period: (*1*) number of portion, (*2*) instrumental epicenters of M ≥ 7.7 main shocks, (*3*) boundary of M ≥ 7.7 earthquake rupture areas determined to within 10 km, (*4*) segments of the same boundaries determined to lower accuracy, (*5*) probable rupture areas of the 1915-1918 M ≥ 7.7 earthquakes, (*6*) the most probable locations of such future earthquakes, (*7*) possible locations of such future earthquakes, (*8*) boundary of prediction portions, (*9*) trench axis, (*10*) epicenters of 5.5 ≤ mb < 6.0 earthquakes for the period March 2001 to March 2006, (*11*) epicenters of mb ≥ 6 earthquakes for the period March 2001 to March 2006, (*12*) isolines of 1 - B for two levels, (*a*) 0.9 and (*b*) 0.7, (*13*) probability of earthquake occurrence P(M ≥ 7.7) for the period April 2006 to April 2011, (*14*) epicenter of the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril earthquake.

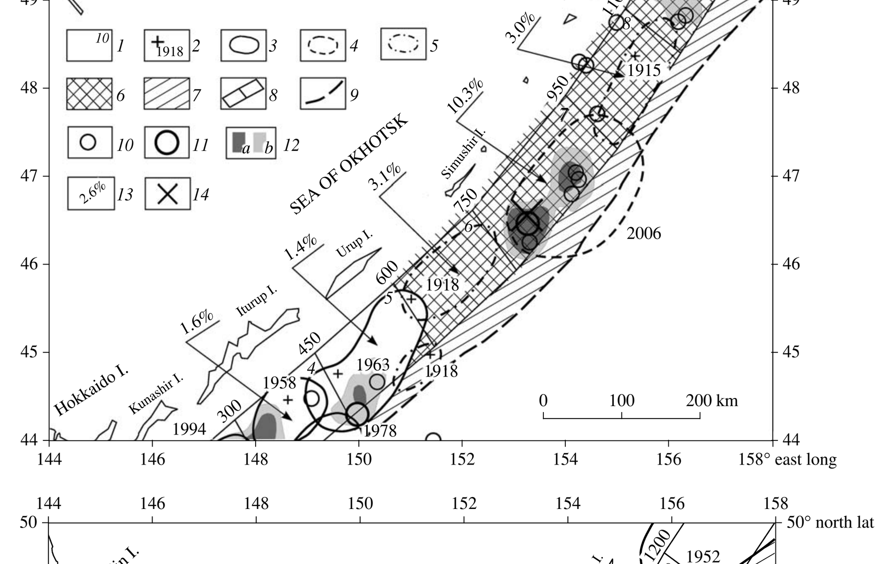

Fig. 4. Map showing the rupture areas of the 1915-2006 M ≥ 7.7 Kuril-Kamchatka earthquakes in the depth range H = 0-80 km, the seismic gaps, isolines of 1-B based on the data between November 15, 2001, and November 14, 2006, as well as earthquake epicenters for that period: (*1*) number of portion, (*2*) instrumental epicenters of M ≥ 7.7 main shocks, (*3*) boundaries of M ≥ 7.7 earthquake rupture areas determined to within 10 km, (*4*) segments of the same boundaries determined to lower accuracy, (*5*) likely rupture areas of the 1915-1918 M ≥ 7.7 earthquakes, (*6*) the most probable locations of future M ≥ 7.7 earthquakes, (*7*) possible locations of such future earthquakes, (*8*) boundary of prediction strip, (*9*) trench axis, (*10*) epicenters of 5.5 ≤ mb < 6.0 earthquakes for the period November 15, 2001, to November 14, 2006, (*11*) epicenters of mb ≥ 6.0 earthquakes for the period November 15, 2001, to November 14, 2006, (*12*) isolines of 1 - B for two levels, (a) 0.9 and (b) 0.7, (*13*) probability of earthquake occurrence P(M ≥ 7.7) for the period November 2006 to November 2011, (*14*) epicenter of the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril earthquake.

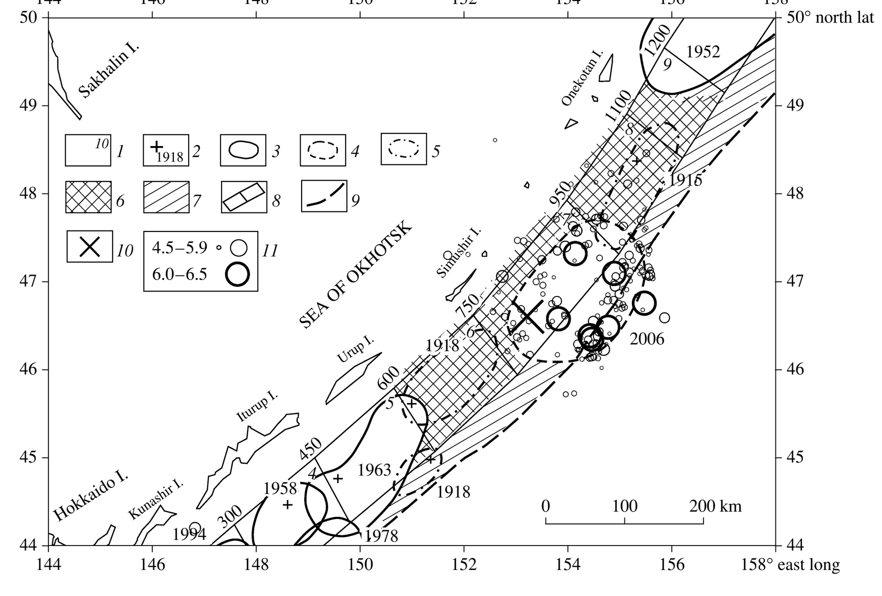

Fig. 5. Map showing the rupture areas of the 1915-2006 M ≥ 7.7 Kuril-Kamchatka earthquakes in the depth range H = 0-80 km, the seismic gaps, as well as aftershocks of the Middle Kuril earthquake: (*1*) number of portion, (*2*) instrumental epicenters of the M ≥ 7.7 main shocks, (*3*) boundaries of M ≥ 7.7 earthquake rupture areas determined to within 10 km, (*4*) segments of the same boundaries determined to lower accuracy, (*5*) likely rupture areas of the 1915-1918 M ≥ 7.7 earthquakes, (*6*) the most probable locations of future M ≥ 7.7 earthquakes, (*7*) possible locations of such future earthquakes, (*8*) boundary of prediction portions, (*9*) trench axis, (*10*) epicenter of the November 15, 2006, M_S = 8.2 Middle Kuril earthquake, (*11*) epicenters of the 10-day mb = 4.5-5.9 and 6.0-6.5 aftershocks.

3. A SUCCESSFUL FORECAST OF THE NOVEMBER 15, 2006, M_S = 8.2 MIDDLE KURIL IS. EARTHQUAKE

When the work on long-term earthquake prediction had just started, and the first map of the Kuril-Kamchatka M ≥ 7.7 earthquakes was being made in 1965, it was found that there were no reliable historical and instrumental data on the occurrence of such earthquakes in the area of the Middle Kuril Is. and Shiashkotan I. (a length of 750-950 km along the Kuril-Kamchatka arc, see Fig. 2). For this reason the area (portion 7) was classified as one of likely locations for future M ≥ 7.7 earthquakes, or seismic gaps [9]; it is bounded on the northeast by the May 1, 1915, M = 8.3 earthquake rupture area and on the southwest by the November 8, 1918, M = 8.2 one (Fig. 2). The boundaries of those rupture areas could only be determined very approximately, from the coordinates of their 4-5 larger aftershocks [1, 9], and were refined later [15] using the catalog [4].

By 2001, more than 80 years had elapsed since these great earthquakes, the current time of the seismic cycle in their rupture areas exceeded 140 - σ = 140 - 60 years, so we classified these locations in 1995-2000 as likely to generate M ≥ 7.7 earthquakes, or seismic gaps. The longest gap then appeared in the Kuril-Kamchatka arc, 500 km long at distances of 650 to 1150 km along the arc, containing portions 6, 7, 8, and 9 in Fig. 2 [12, 16 and elsewhere].

This portion of the Kuril island arc exhibits several features that distinguish it from the southern and northern parts, the South and North Kuril Islands. There is no outer island arc like the Lesser Kuril chain in the south, no great earthquakes have been recorded, and the crustal structure is different. Based on these and some other features of this area, some investigators believed that the maximum earthquake magnitude cannot exceed M = 7.5±0.2 there [5, 8 and elsewhere].

However, the leading tectonic feature is continuous along the entire Kuril-Kamchatka arc and its Kuril part; it consists of a deep-sea trench, a continuous Benioff zone, and the volcanic belt. There are also transverse faults cutting across the arc, and other features in its tectonic structure. However, the rupture areas of M = 7.7-8.5 earthquakes have dimensions between 100 and 600 km. These areas, as considered in our long-term prediction method, are superposed upon smaller tectonic features. Long-term forecasts as developed for large portions of the Kuril-Kamchatka arc assume, to a first approximation, that the arc is a homogeneous extended seismotectonic structure and the seismicity in different large portions of the arc, its segments 100-200 km long or longer, is the same.

On November 15, 2006, the M_W = 8.3, M_S = 8.2 Middle Kuril earthquake occurred, and its rupture area filled the entire seismic gap in portion 7 (Figs. 2-6). This event proved that M ≥ 7.7 earthquakes can occur in the Middle Kuril Islands area.

The increased probability of a great earthquake in the area of the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril Is. earthquake has invariably been predicted since 1965. The associated gap was marked as such in the first (1965) map of M ≥ 7.7 earthquake rupture areas and the likely locations of future events this size in the Kuril-Kamchatka seismogenic zone [9]. Afterwards this seismic gap, portion 7, distance 750 to 1000 km (750-950 km in Fig. 2), was indicated as one of the most likely locations of future M ≥ 7.7 earthquakes in the five-year long-term forecasts published for 1965-1970, 1971-1975, and the subsequent five intervals, until and including 1996-2000 [9, 12, 14, 15 and elsewhere]. The relative hazard of portion 7 was estimated in 1965-2005 from the five-year data using the parameter B = P(A_{10}) × P(D) [12, 16 and elsewhere]. In 1965-2000 portion 7 was the third by hazard level in 3 of 7 cases among the 6-7 gaps that were available during that period, and among all the twenty identified portions of the seismogenic zone. Based on the data for April 2001 to March 2006, concerning the relative hazard of the seismic gaps using the parameter B = P(A_{10}) × P(D) × P(A_{11}) and incorporating the size of portions L (Table 1), portion 7 has become the fifth among the twenty by hazard level in the entire Kuril-Kamchatka arc, and the first among the four portions (6-9), which make a seismic gap 550 km long off the Middle Kuril Islands and Shiashkotan I. (Fig. 2, Table 1).

According to the long-term forecast for the Kuril-Kamchatka arc, the period April 2006 to April 2011 (Table 1, Fig. 2), the highest probability of an M ≥ 7.7 earthquake was in the Petropavlovsk-Kamchatskii area, in portions 11*b*, 12*b*, and 13*a* (Fig. 2). The seismic gaps available there extend for 450 km along the Kuril-Kamchatka arc. The total probability of earthquake occurrence in these portions is ΣP(M ≥ 7.7) = 16.8 + 14.6 + 10.4 = 41.8 %. Those posing the greatest hazard are portions 11*b* and 12*b* situated off southern Kamchatka and in the Avacha Bay in the Petropavlovsk-Kamchatskii area.

The total probability of an M ≥ 7.7 earthquake in the other major gap, off the Middle Kuril Islands and Shiashkotan I. (portions 6-9, Fig. 2), was ΣP(M ≥ 7.7) = 3.0 + 9.6 + 3.5 + 8.6 = 24.7 %; among these, portion 7 was the most dangerous according to the forecast. It was in this portion that the M_W = 8.3, M_S = 8.2 Middle Kuril earthquake occurred on November 15, 2006 (Figs. 3-5). That was another confirmation that the long-term prediction for the Kuril-Kamchatka arc in progress since 1965 is reliable [9, 10, 12]. This was the seventh time since 1965 that the forecast of the next-to-occur M ≥ 7.7 earthquake was correct. The event again occurred in an identified seismic gap. In the case under consideration, the instrumental epicenter and the aftershocks of the November 15, 2006, earthquake were a neat fit between the rupture areas of the May 1, 1915, M = 8.1 and the September 7, 1918, M = 8.3 earthquakes (Figs. 2 through 5).

Again, as had been the case with the October 13, 1994, M = 8.0 Shikotan [19] and the December 5, 1997, M = 7.9 Kronotskii [18, 22] earthquakes, this great quake occurred in the gaps that had been considered to present the highest hazard.

These results corroborate the long-term earthquake forecast for the Kuril-Kamchatka arc, highlighting the Petropavlovsk-Kamchatskii area as the most likely location for a next M ≥ 7.7 earthquake. The most fortunate thing was that this great Kuril-Kamchatka earthquake occurred off the nearly unpopulated Middle Kuril Islands rather than near the largest town in Kamchatka and the Kuril Islands, namely, Petropavlovsk-Kamchatskii, where it could have caused very grave consequences.

4. THE LONG-TERM FORECAST FOR THE KURIL-KAMCHATKA ARC FOR THE PERIOD NOVEMBER 20, 2006, TO OCTOBER 2011

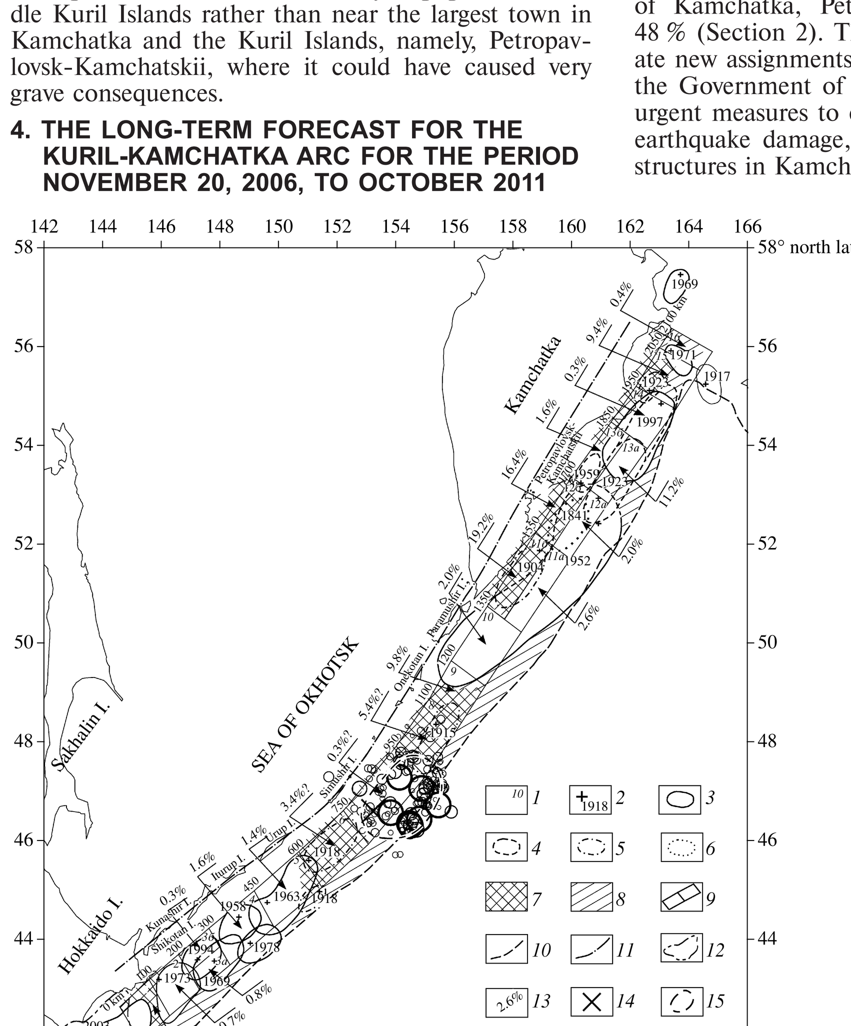

Fig. 6. Map showing the long-term forecast for the Kuril-Kamchatka arc for the period November 20, 2006, to October 2011 as updated after the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril earthquake, the rupture areas of the 1904-2006 M ≥ 7.7 Kuril-Kamchatka earthquakes in the depth range H = 0-80 km, and the probabilities of occurrence for such earthquakes for the period December 2006 to October 2011 in all portions of the prediction strip: (*1*) number of portion, (*2*) instrumental epicenters of M ≥ 7.7 main shocks, (*3*) boundaries of M ≥ 7.7 earthquake rupture areas determined to within 10 km, (*4*) segments of the same boundaries determined to lower accuracy, (*5*) likely rupture areas of the 1904-1918 M ≥ 7.7 earthquakes, (*6*) inferred rupture area of the 1841 earthquake, (*7*) the most probable locations of future M ≥ 7.7 earthquakes, (*8*) possible locations of such future earthquakes, (*9*) boundary of prediction portions, (*10*) trench axes, (*11*) axis of the Kuril-Kamchatka volcanic belt, (*12*) boundary of the September 25, 2003, M = 8.1 earthquake rupture area, (*13*) probabilities of M ≥ 7.7 earthquakes for the period November 20, 2006, to October 2011, (*14*) epicenter of the November 15, 2006, M_S = 8.2 Middle Kuril earthquake, (*15*) preliminary boundary of its rupture area, (*16*) epicenters of the 10-day mb = 4.5-5.9 aftershocks, (*17*) epicenters of the 10-day mb = 6.0-6.5 aftershocks. The average probability of occurrence for M ≥ 7.7 Kuril-Kamchatka earthquakes at the same location during 5 years is equal to 3.6-4.2 %.

past 80 years and the seismic gaps between them; the seismogenic zone is divided into about 20 portions, depending on the locations of these rupture areas and seismic gaps (Sections 1, 2, and 4). For these portions, 50 × 100 to 100 × 200 km in size, we predict for five-year intervals the following: the phase of the seismic cycle, seismicity rate A_{10}, earthquake magnitudes to be expected with probabilities 0.8, 0.5, and 0.15, the maximum credible magnitude, the probability of great earthquakes P(M ≥ 7.7), the most likely locations of the next M ≥ 7.7 earthquakes (seismic gaps), and the relative hazard of the seismic gaps.

The estimate of relative hazard to be ascribed to the seismic gaps, P(M ≥ 7.7), is an important part of the forecast. The mean repeat time between successive M ≥ 7.7 earthquakes in the Kuril-Kamchatka arc as a whole is close to 5 years, the mean interevent interval was equal to 5.6±4.4 years. The estimates for the probabilities of the next M ≥ 7.7 earthquakes in different portions of the seismogenic zone were calculated assuming such quakes to be mutually exclusive events the sum of whose probabilities is one. These estimates are relevant to the next 5-year interval. Taking 11 five-year intervals between M ≥ 7.7 earthquakes in 1952-2006, one or two M ≥ 7.7 quakes occurred in nine cases of the eleven, and the assumed condition was satisfied in more than 0.8 of the cases (Sections 1, 2, 4, and 5).

The forecasts made during the period 1965-2000 have been successful in 0.8-0.9 of the cases [12 and elsewhere]. If the recent 12-year interval is considered, the forecasts were successful for the locations of the October 13, 1994, magnitude 8.1 Shikotan earthquake [20] and the December 5, 1997, magnitude 7.9 Kronotskii earthquake [17, 23]. A new success came with the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril earthquake (Section 3).

(3) Ever since the beginning (in the year 1965) of seismological research using the long-term method here considered, the major seismic gap in the Middle Kuril Is. area has been regarded as a likely location of future M ≥ 7.7 earthquakes to be expected along the Kuril-Kamchatka arc [9, 12 and elsewhere]. Several investigators believed that no earthquakes larger than 7.5±0.2 could occur there. Also later, we identified the area of the Middle Kuril Is. and Shiashkotan I. as one of the most hazardous seismic gaps [12, 14, 15, 16 and elsewhere]. The last forecasts to this effect were made twice in the year 2006 – in April and again in October – just before the event in question (Figs. 2 and 6, Section 3).

The November 15, 2006, earthquake rupture area is a very accurate fit to the predicted seismic gap.

(4) The long-term forecast for the Kuril-Kamchatka arc for the period April 2006 to April 2011 (Section 2) was another confirmation that the greatest earthquake hazard existed for the Petropavlovsk-Kamchatskii area where the total probability of an M ≥ 7.7 earthquake in six contiguous portions (11*a*, 11*b*, 12*a*, 12*b*, 13*a*, and 13*b* in Fig. 2; Table 1) capable of causing shaking of intensity VII to IX at Petropavlovsk-Kamchatskii was as high as 48 % (Section 2).

The area with the second highest level of earthquake hazard was that of the Middle Kuril Is. and Onekotan I. (portions 6-9 in Figs. 2 and 4) where the total probability P(M ≥ 7.7) reached 26.7 % (Section 2).

The forecast was found to have been successful when the November 15, 2006, M_W = 8.3, M_S = 8.2 Middle Kuril earthquake occurred there (Section 3).

After that event we made an update of the long-term forecast for the period November 2006 to October 2011 (Section 4), which will be more reliable for the Middle Kuril Is. area when aftershock data for the first year following the November 15, 2006, earthquake become available. The probability of an earthquake causing ground motions of intensity VII-IX at Petropavlovsk-Kamchatskii has increased to a level as high as 53 % (Section 4). The probability of an earthquake in the Avacha Bay, which can produce shaking of intensity IX at Petropavlovsk-Kamchatskii, is equal to 16.5 % (Sections 4 and 5, Fig. 6).[1]

The next most hazardous areas are the Nemuro Peninsula, portion 1 (Fig. 6) where P(M ≥ 7.7) = 11.2 %; the Kamchatskii Bay in Kamchatka, portion 15 (Fig. 6) where P(M ≥ 7.7) = 9.4 %; and lastly, the Onekotan I. area northeast of the November 15, 2006, earthquake rupture area, portion 9 (Fig. 6) where P(M ≥ 7.7) = 9.8 %.

At the same time, half of the portions of the Kuril-Kamchatka seismogenic zone have probabilities of great M ≥ 7.7 earthquakes equal to the average (3.6-4.2 %) or considerably (by factors of 10-15) lower.

(5) The 1986-2006 long-term earthquake forecasts for the Kuril-Kamchatka arc were a basis for six government decrees on measures to be taken to enhance the earthquake preparedness of Kamchatka Region, see [12]. According to the April 2006 to April 2011 long-term forecast for the Kuril-Kamchatka arc, the probability of earthquakes causing ground motions of intensity VII-IX during that period at the largest town of Kamchatka, Petropavlovsk-Kamchatskii, reached 48 % (Section 2). The forecast was used to substantiate new assignments and decrees of the President and the Government of the Russian Federation regarding urgent measures to enhance seismic safety, to prevent earthquake damage, and to strengthen buildings and structures in Kamchatka Region.

CONCLUSION

(1) Results are discussed from the 2005-2006 work on long-term earthquake prediction for the Kuril-Kamchatka arc; this work relies on a method based on the patterns of seismic gaps and the seismic cycle [9, 10, 12, 14, 21, 25, and elsewhere]. We provide information on the method and its developments, present long-term forecasts for the Kuril-Kamchatka arc for the period April 2006 to April 2011 (Section 2) made in April 2006 before the November 15, 2006, Middle Kuril earthquake of M_W = 8.3, M_S = 8.2; and the forecast for the period November 2006 to October 2011 (Section 4) as of November 19, 2006, after the earthquake, which incorporates the changes wrought by that event in the seismic process.

(2) Similarly to previous work using the method described in [12, 14 and elsewhere], we delineate the rupture areas of M ≥ 7.7 earthquakes that have occurred in the Kuril-Kamchatka seismogenic zone during the

The long-term forecast developed here is also a long-term forecast of tsunami probability in various areas of the Kuril-Kamchatka arc.

(6) The above results show that the present long-term earthquake prediction method can be used for other regions worldwide that have similar structures and extended seismogenic zones.

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[1] *The M_S = 8.2 earthquake which occurred January 13, 2007, in the rupture area of the November 15, 2006, Middle Kuril earthquake, demonstrated that the long-term forecast for the Middle Kuril Islands can be updated. However, no reasons were found immediately after the occurrence of that earthquake for a significant revision of these earthquake probabilities capable of producing ground motions of intensity VII–IX at Petropavlovsk-Kamchatskii.*

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